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An Experimental Study and Modeling of the Field Emission Properties of an Isolated Individual Multi-Walled Carbon Nanotube

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The stable chemical structure, low turn-on fields, and high current densities of carbon nanotubes (CNTs) make this class of material highly desirable for cold field emission applications. Carbon nanotube films are being developed as electron beam sources in commercial products such as flat panel field emission displays, field emission lamps, and X-ray tubes. The isolated individual CNT has been proposed for use as an advanced cold field emitter for electron microscope applications. One of the many advantages of the CNT in comparison to conventional emitters is its low electron beam energy spread, which is important for improving microscope resolution. This paper reports experimental data for individual multi-walled CNT (MWNT) emitters. For comparison, a thermodynamics-based variational method was used to obtain a closed-form expression for the radial electric field of a spherical cathode. Theoretical data generated from Technology Computer-Aided Design (TCAD) device simulation software is also reported. A fundamental understanding of the individual CNT emitter has important ramifications for electron microscope applications. Developing theoretical models for nanotube field emission properties using a thermodynamics-based variational approach [1] as well as TCAD [2] would provide design rules for optimizing carbon nanotube film emitters for various applications.

An SEM image of an individual MWNT field emitter is shown in Fig. 1a. Our lab has developed a highly reproducible fabrication method for these single MWNT devices [3], whereby the MWNT structural parameters

such as diameter to length aspect ratio could be simply modified for systematic studies. With a separation of $74 \pm 2 \mu\text{m}$ between the nanotube tip (cathode) and the extractor (anode), the current I was measured as a function of the extraction voltage U as shown in Fig. 1b. Field emission began at $U \cong 110 \text{ V}$, giving a very small macroscopic field of $F_m = 1.5 \times 10^6 \text{ V/m}$ for the initial onset of emission. The linear profile of this data clearly indicates Fowler-Nordheim (F-N) cold field emission behavior as illustrated in Fig. 1c. Numerical analysis using the F-N equation gives a field enhancement factor of $\gamma = 2738$, a work function $q\phi = 5.1 \text{ eV}$, and MWNT tip radius of curvature $R = 26 \text{ nm}$. Based on the field enhancement factor, the electric field at the tip F_t is $4.1 \times 10^9 \text{ V/m}$.

The field emission characteristics of the individual MWNT field emitter shown in Fig. 2a are being investigated as a function of cathode-anode separation, d . Here, d is defined as the distance between the end of the MWNT and the opposing planar anode. Current-voltage data were collected for $d = 10 \mu\text{m}$ to $250 \mu\text{m}$, with a $10\text{-}\mu\text{m}$ difference between successive voltage sweeps. The current-voltage characteristics for the emitter for $d = 10 \mu\text{m}$ to $80 \mu\text{m}$ are displayed in Fig. 2b. The current-voltage profile is more abrupt for small d , when compared to the case for large d , because the emitting area of the MWNT tip increases as d decreases. Fig. 2c illustrates the corresponding turn-on voltages and the macroscopic turn-on fields for the various cathode-anode separations. Similar data for several individual MWNT emitters are presently being compared to developing theoretical models in order to understand MWNT field emission behavior for various separations.

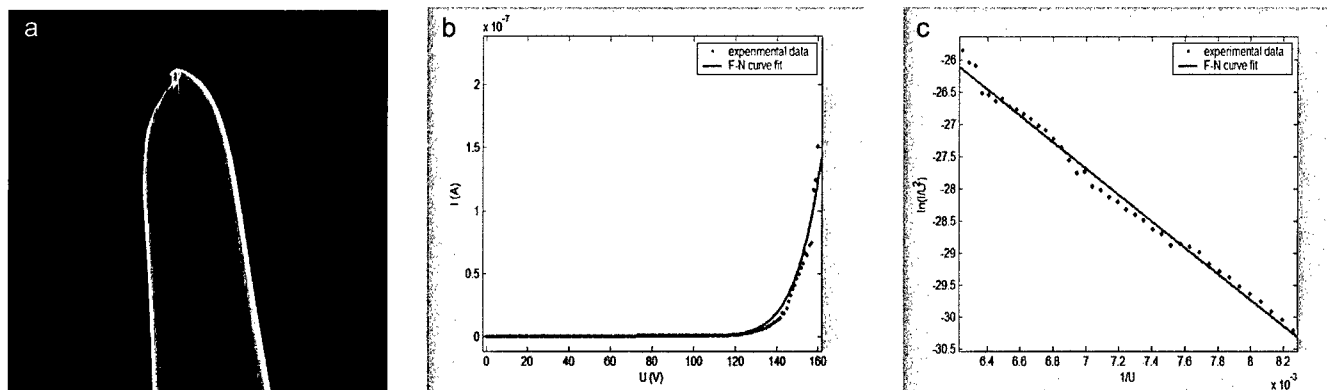


Figure 1. (a) Scanning electron microscopy (SEM) image of a multi-walled carbon nanotube (MWNT) attached to an electrochemically etched nickel wire. (b) Current-voltage field emission data of the MWNT in (a), with the Fowler-Nordheim equation curve fit. (c) Fowler-Nordheim plot of the same data.

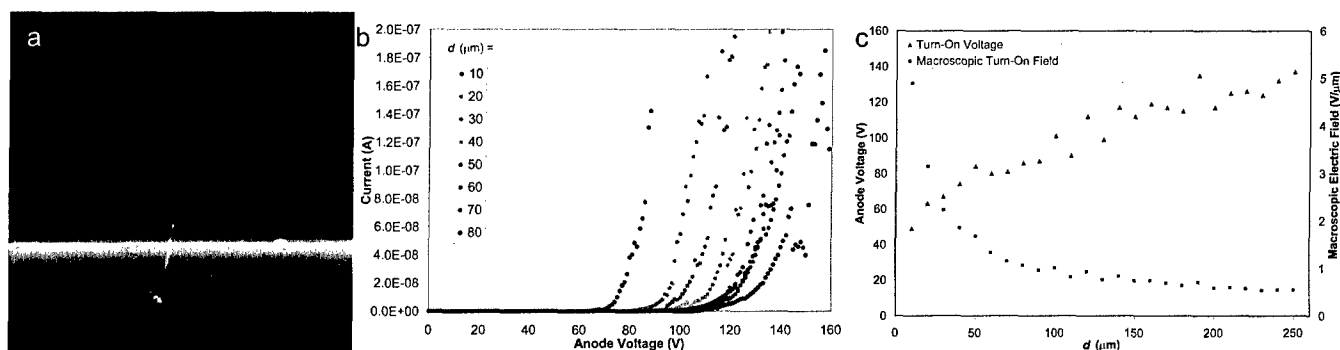


Figure 2. (a) Scanning electron microscopy (SEM) image of a multi-walled carbon nanotube (MWNT) attached to a nickel-coated silicon microstructure. (b) Current-voltage field emission data of the MWNT in (a) for various cathode-anode separations, d . (c) Turn-on voltage (red) and macroscopic turn-on field (blue) versus d for the same MWNT.

The thermodynamics-based variational calculation of the electrostatic field surrounding a spherical metallic emitter of radius a , held at potential V , and at a distance l from a grounded planar anode (Fig. 3), gives the following expression for the magnitude of the radial electric field in spherical coordinates:

$$\vec{E}_r = V \left[1 + \frac{a \cos \theta}{l} \right] \frac{a}{r^2}$$

Here, $0 \leq \theta \leq \pi/2$ and $a \leq r \leq l$. The expression above predicts that the voltage at onset of emission should decrease with decreasing separation l between emitter tip and anode as:

$$V_0 = \frac{\text{const.}}{1 + \frac{a}{l}}$$

For a spherical cathode with radius 26 nm, these expressions predict a turn-on field at the tip of $F_t = 4.2 \times 10^9$ V/m. This agrees very well with the corresponding field of 4.1×10^9 V/m found experimentally for the MWNT emitter in Fig. 1.

Silvaco's device simulation package is also employed to develop a TCAD-based model for CNT field emission. Preliminary field emission characteristics of a nanostructure with a hemispherical cap have been simulated and are schematically illustrated in Fig. 4. The simulated structure has a supporting substrate with a radius of 2 μm, a 1-μm long nanostructure that consists of a stalk with a 26-nm radius, and a hemispherical cap also with a radius of 26 nm. A TCAD Fowler-Nordheim model was adjusted to fit the experimental data in Fig. 1 for a 75-μm cathode-anode separation. The resulting calibrated F-N model was used to explore the impact of cathode-anode separation on the turn-on voltage of the nanostructure. The results of this study are shown in Fig. 3b, exhibiting a decreasing turn-on voltage with smaller cathode-anode separation, corresponding to a macroscopic field ranging from 2×10^6 V/m to 1.5×10^6 V/m for cathode-anode separations of 5 μm to 75 μm, respectively. Details of the electric field at the nanostructure tip and factors determining current density are under investigation.

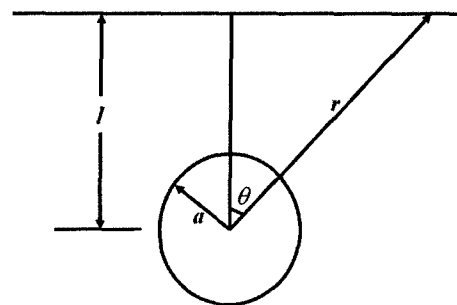


Figure 3. A schematic representation of a spherical metallic cathode of radius a and at a distance l from a planar anode. The cathode is held at potential V with respect to the grounded anode.

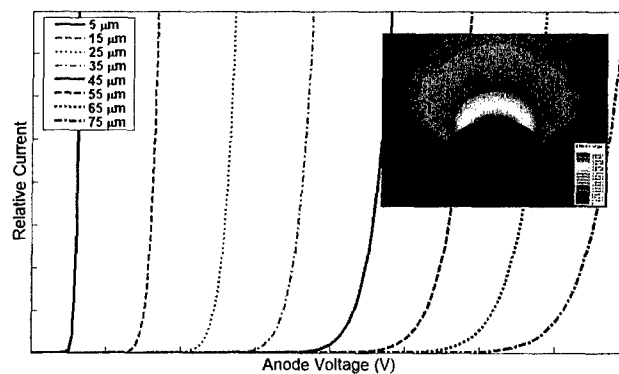


Figure 4. Comparison of turn-on voltages for various cathode-anode separations using the calibrated Fowler-Nordheim model. Inset shows the structure studied with an overlay showing a contour plot of the electric field surrounding the tip.

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